

Tidal streams from axion miniclusters and direct axion searches

Peter Tinyakov^a Igor Tkachev^b Konstantin Zioutas^c

^aUniversite Libre de Bruxelles, Service de Physique Theorique, CP225, 1050, Brussels, Belgium

^bInstitute for Nuclear Research of the Russian Academy of Sciences, Moscow 117312, Russia

^cUniversity of Patras, Greece and CERN, Geneve, Switzerland

Abstract. In some axion dark matter models a dominant fraction of axions resides in dense small-scale substructures, axion miniclusters. A fraction of these substructures is disrupted and forms tidal streams where the axion density may still be an order of magnitude larger than the average. We discuss implications of these streams for the direct axion searches. We estimate the fraction of disrupted miniclusters and the parameters of the resulting streams, and find that stream-crossing events would occur at a rate of about $1/(20\text{yr})$ for 2-3 days, during which the signal in axion detectors would be amplified by a factor ~ 10 . These estimates suggest that the effect of the tidal disruption of axion miniclusters may be important for direct axion searches and deserves a more thorough study.

Contents

1	Introduction	1
2	Axion Miniclusters	2
3	Tidal destruction of miniclusters by stars	3
4	Axion streams and implications for direct axion searches.	4
5	Conclusions	5
6	Acknowledgments	7
7	Bibliography	7

1 Introduction

In a wide variety of axion Dark Matter (DM) models, a sizable (or even dominant) fraction of axions is confined in a very dense axionic clumps, or miniclusters, with masses $M \sim 10^{-12} M_\odot$. The axion miniclusters originate from specific density perturbations which are a consequence of non-linear axion dynamics around the QCD epoch [1–3]. There may be $\sim 10^{24}$ of such miniclusters in the Galaxy, their density in the Solar neighborhood being $\sim 10^{10} \text{ pc}^{-3}$. Typical miniclusters have radius of $\sim 10^7 \text{ km}$ and the density $\sim 10^8 \text{ GeV cm}^{-3}$. During a direct encounter of the laboratory with such a minicluster the local axion density increases by a factor of 10^8 for about a day. That would create a very strong signal in the tuned detectors devoted to direct axion searches. However, direct encounters with the Earth would occur only once in $\sim 10^5$ years [4].

Over the lifetime of the Galaxy, the axion miniclusters may be tidally disrupted forming tidal streams. In this paper we discuss possible phenomenological consequences of these structures for the direct axion searches. As we will argue, the tidal streams have a much larger volume than the original miniclusters, which boosts the encounter rate. At the same time they may still be dense enough to produce a sizable signal in axion detectors.

A similar idea has already been discussed in a general context of weakly interacting massive particles (WIMPs). In any cold dark matter model (including WIMPs and axions) halos are formed, by a standard gravitational instability, on all scales from galaxies down to a free-streaming scale, leading to structure formation from primordial density perturbations. In case of WIMPs, the smallest halos have masses around $M \sim 10^{-7} M_\odot$ as set by the free streaming scale in a typical WIMP model [5–7]. For the axion DM the minihalos form down to even smaller masses $M \sim 10^{-12} M_\odot$, which is the mass of all axions inside the horizon at the epoch when the axion oscillations commence. This process has been numerically modeled both for WIMPs and axions in Ref. [8] in the mass range $10^{-6} M_\odot \lesssim M \lesssim 10^{-4} M_\odot$. For minihalos with $M \sim 10^{-6} M_\odot$ their density in the Solar neighborhood after formation was found to be $\sim 500 \text{ pc}^{-3}$, the direct encounter with the Earth would occur once in 10^4 years, and during the encounter the DM density would increase by a factor of 100 over the average for about 50 years. However, virtually all minihalos which are crossing Solar neighborhood

are tidally destroyed long before the present epoch [7, 9–12] producing a density field not interesting for the direct detection of DM [13]. The situation may be different for axion miniclusters due to an additional, different formation mechanism that leads to smaller and denser clumps, the axion miniclusters.

2 Axion Miniclusters

Unlike other forms of DM, axions may develop density fluctuations of order one (or even larger) already at early times, prior to radiation-matter equality. This happens due to a peculiar (non-linear) axion dynamics at the epoch when axion oscillations commence. Let us denote by $\Phi = \delta\rho_a/\rho_a$ the energy density contrast in the axion field at the end of this epoch. Consider the class of models where Peccei-Quinn symmetry is restored during reheating or preheating after inflation. Then the ratio $\theta = a/f_a$, where a is the axion field and f_a the axion decay constant, can take any value from one horizon volume to another, while being smooth within a given horizon. When the axion oscillations start due to development of a non-zero axion potential $V(\theta) = m_a^2 f_a^2 [1 - \cos(\theta)]$ at the beginning of the QCD epoch, the field fluctuations $\delta\theta \sim 1$ are transformed into density fluctuations $\Phi \sim 1$. Numerical investigations of the dynamics of the axion field at this epoch [2–4, 14] have shown that the non-linear effects lead to clumps with Φ much larger than unity, possibly as large as several hundred. These regions separate from cosmological expansion at temperature $T \simeq \Phi T_{\text{eq}}$, where T_{eq} is the temperature of equal matter and radiation energy densities. This results in a final minicluster density today given by [4]

$$\rho_{\text{mc}} \simeq 7 \times 10^6 \Phi^3 (1 + \Phi) \text{ GeV/cm}^3. \quad (2.1)$$

This should be compared to the mean DM density in the Solar neighborhood in the Galaxy, $\bar{\rho} \approx 0.3 \text{ GeV/cm}^3$.

The scale of minicluster masses is set by the total mass M_1 of axions within the Hubble radius at a temperature around $T \approx 1 \text{ GeV}$ when axion oscillations start,

$$M_1 \approx 10^{-12} M_\odot. \quad (2.2)$$

Numerical integration of Ref [14] shows that a spectrum of minicluster masses is produced that is compact and concentrated around a sizable fraction of M_1 , so that $0.1M_1 \lesssim M_{\text{mc}} \lesssim M_1$. In what follows, however, we do not rely on this spectrum. Instead, we assume a single value of $M_{\text{mc}} = 10^{-12} M_\odot$ for simplicity, except for our final result, Fig. 2, which is presented for two bracketing values $M_{\text{mc}} = 10^{-12} M_\odot$ and $M_{\text{mc}} = 10^{-13} M_\odot$.

The minicluster radius as a function of Φ and M_{mc} is

$$R_{\text{mc}} \approx \frac{3.4 \times 10^7}{\Phi (1 + \Phi)^{1/3}} \left(\frac{M_{\text{mc}}}{10^{-12} M_\odot} \right)^{1/3} \text{ km}, \quad (2.3)$$

while the typical virial velocity in the minicluster, $v_{\text{mc}}^2 = GM_{\text{mc}}/R_{\text{mc}}$ is given by

$$v_{\text{mc}} \approx 2.1 \times 10^{-10} \Phi^{1/2} (1 + \Phi)^{1/6} \left(\frac{M_{\text{mc}}}{10^{-12} M_\odot} \right)^{1/3}. \quad (2.4)$$

The distribution of miniclusters in values of Φ has been calculated numerically in Ref. [14] neglecting contribution from the decaying axion strings and domain walls. This

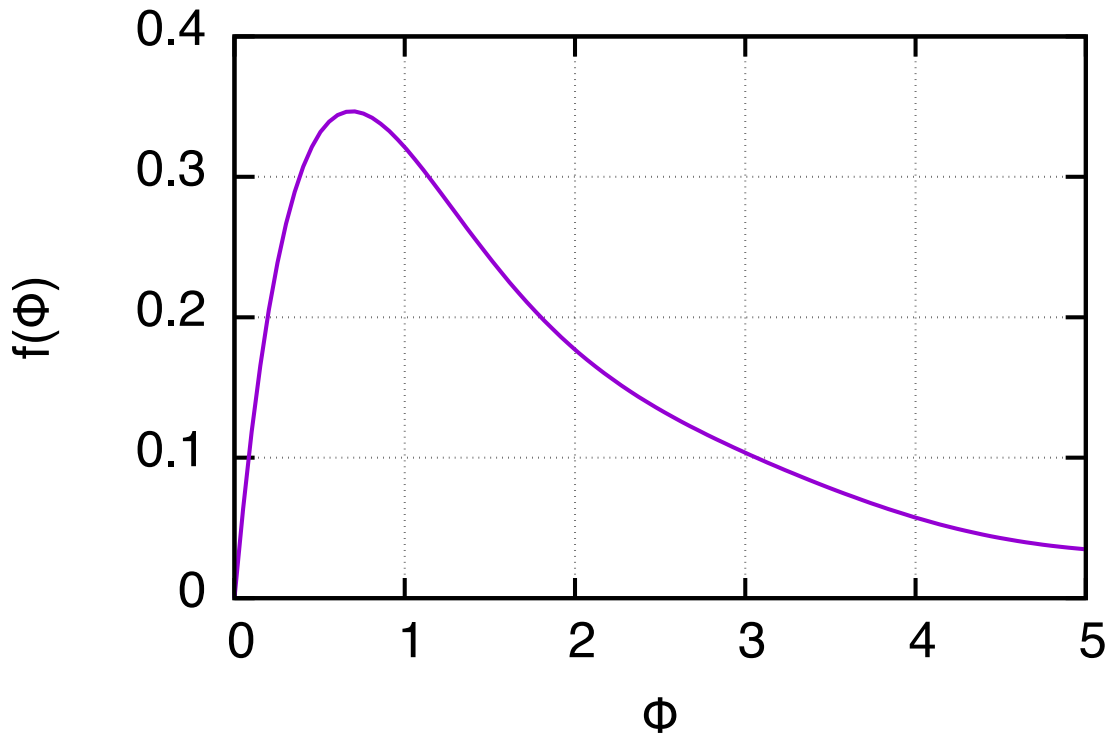


Figure 1. Mass fraction $f(\Phi)$ of axions in miniclusters with a given value of Φ .

distribution is summarized in Fig. 1 which shows a differential probability $f(\Phi)$ to find an axion in a clump with a given value of Φ , as a function of Φ . According to this plot, 70% of all axions are in miniclusters with $\Phi > 1$. Contribution from the decay of the domain wall -string network is likely to modify this distribution only quantitatively. Indeed, since i) the axion string network decays completely at the epoch when the axion oscillations start ii) the process is highly inhomogeneous being dominated by the horizon scale iii) produced axions are non-relativistic, see e.g. [15], one can expect that the change in the minicluster distribution will not be qualitative.

3 Tidal destruction of miniclusters by stars

Small-scale clumps in the Galaxy may be tidally disrupted by the gravitational field of the halo, of the disc and in encounters with stars. These processes were studied by many authors, for a review see [7]. The axion miniclusters are too dense to be disrupted by the halo gravitational field. Here we estimate the rate at which they are disrupted in stellar encounters, which is the dominant process for the relevant range of masses.

When a minicluster traverses the stellar field, interactions with individual stars increase the velocity dispersion of dark matter particles and reduce the clump's binding energy. Following Refs. [12, 13] we introduce a critical impact parameter, b_c , such that for $b < b_c$ a single encounter is sufficiently strong to unbind the minicluster. This parameter was found to be [12, 13]

$$b_c^2 \approx \frac{GM_s R_{mc}}{v_{rel} v_{mc}}, \quad (3.1)$$

where v_{rel} is the relative velocity of a minicluster and a star, and M_s is the star mass. Therefore, the disruption cross section in such a “strong” encounter is πb_c^2 and is proportional to the star mass. The break-up probability in a single passage of a minicluster through the Galactic disc is

$$p_s = \pi \frac{GR_{\text{mc}}}{v_{\text{rel}} v_{\text{mc}}} S, \quad (3.2)$$

where S is the column mass density of stars. Note that, because of eq. (3.1), only the total star mass density enters this expression, while the distribution of stars in masses drops out. Also, p_s does not depend on minicluster mass, cf. eqs. (2.3) and (2.4).

According to Ref. [16] the stellar contribution to the column density is $S_{\perp} \approx 35 \text{ M}_{\odot} \text{pc}^{-2}$ in the direction orthogonal to the disc, and correspondingly larger for the inclined directions. We are interested in minicluster trajectories which pass through the vicinity of the Earth. Assuming for the sake of the estimate that such trajectories are distributed isotropically, the integral over the angles diverges logarithmically when approaching the direction parallel to the disk; it has to be cut at the typical length of the trajectory that lies completely in the disk, for which we take $O(10 \text{ kpc})$. Integration over directions then gives

$$S \approx 4S_{\perp}.$$

The cumulative effect of multiple non-disruptive encounters with $b > b_c$ increases the disruption probability by a factor of about two [12], $P = 2p_s$.

To estimate the total probability of a minicluster disruption until the present epoch we multiply the disruption probability in a single crossing of the disk by the number of crossings over the whole history of the Galaxy, $n \sim 100$. Assuming $v_{\text{rel}} = 10^{-3}$ in eqs. (3.2) we find

$$P(\Phi) = 0.022 \left(\frac{n}{100} \right) \Phi^{-3/2} (1 + \Phi)^{-1/2}. \quad (3.3)$$

Only a few percent of miniclusters with $\Phi \sim 1$ are destroyed, the rest remain intact. However, even this small fraction of disrupted miniclusters may be important for direct axion searches.

4 Axion streams and implications for direct axion searches.

Debris from disrupted miniclusters form tidal streams along the minicluster trajectory. For orbits with small ellipticity the streams are essentially one-dimensional structures of large length L and cross-section comparable to the initial clump size. Recently this process was modeled for clumps with $M \sim 10^{-6} M_{\odot}$, see Ref. [13, 20], while for the general theory and arbitrary orbits see e.g. Refs. [17–19].

Following Ref. [13] we estimate the length of the tidal streams due to the orbiting process as $L \sim v_{\text{mc}} t$, where t is the age of a stream. In this approximation, when a minicluster is disrupted and forms a tidal stream, its volume grows by a factor $v_{\text{mc}} t / R_{\text{mc}}$. The axion density in the stream drops accordingly,

$$\rho_{\text{st}}(\Phi) = \rho_{\text{mc}} \frac{R_{\text{mc}}}{v_{\text{mc}} t}, \quad (4.1)$$

and does not depend upon minicluster mass.

The time τ to cross such a stream by an observer moving with the relative velocity v_{rel} does not depend on the stream age,

$$\tau(\Phi, M_{\text{mc}}) = 2R_{\text{mc}}/v_{\text{rel}} \approx$$

$$\approx 62 \text{ hr } \Phi^{-1} (1 + \Phi)^{-1/3} (M_{\text{mc}}/10^{-12} M_{\odot})^{1/3}. \quad (4.2)$$

In the context of axion detection, this time interval corresponds to a period of high signal in the detector. As this signal is proportional to the axion density, it is convenient to introduce the *amplification factor*

$$A = \rho_{\text{st}}/\bar{\rho}. \quad (4.3)$$

The value $A = 0$ corresponds to no signal amplification during the string crossing event.

If the disrupted miniclusters had the same axion density and were disrupted at the same time, all resulting streams would have the same axion density. Knowing the volume filling factor of these streams in the Galaxy ϵ and the crossing time τ , the frequency of the stream-crossing events would then be

$$\nu = \frac{\epsilon}{\tau}. \quad (4.4)$$

The meaning of ν is that the mean number of stream-crossings in a given time interval Δt is $N = \nu \Delta t$. It is important to note that ν is proportional to ϵ and therefore contributions to ν of different types of miniclusters can be simply added.

In a realistic situation the miniclusters are distributed in Φ (and, therefore, in density) as follows from Fig. 1. The disruption probability of a minicluster also depends on Φ , cf. eq. (3.3). Moreover, the miniclusters of a given Φ can be disrupted at different times, which are distributed uniformly from the moment of the Galactic stellar disc formation until present; they would then produce streams of a different density. The contribution into the stream-crossing rate of streams of a given amplification factor A originated from miniclusters of given Φ can be written as follows:

$$d\nu = \frac{P(\Phi)f(\Phi)}{\tau(\Phi, M_{\text{mc}})} \frac{a(\Phi)}{A^3} dA d\Phi. \quad (4.5)$$

Here $f(\Phi)$ is the mass fraction in miniclusters, Fig. 1, $P(\Phi)$ and $\tau(\Phi, M_{\text{mc}})$ are given by eqs. (3.3) and (4.2), and $a(\Phi) = \rho_{\text{st}}(\Phi)/\bar{\rho}$ is the amplification factor corresponding to the minicluster with given Φ disrupted right after the Galactic disk formation as given by eq. (4.1) with t equal to the age of the disk. The physically relevant quantities are obtained by integrating eq. (4.5) over appropriate range. It is convenient to introduce $\nu(A)$ as a frequency of stream crossings with the amplification larger than the given value A . To obtain $\nu(A)$, eq. (4.5) has to be integrated over A from $\max(A, a(\Phi))$ to $\rho_{\text{mc}}/\bar{\rho}$ as determined by eq. (2.1), and over Φ .

To characterize the prospects of axion detection in encounters with tidal streams, we present in Fig. 2 the mean number of stream encounters $N(A) = \nu(A)\Delta t$, where the observation time interval was taken to be $\Delta t = 20$ yr. The upper pair of curves (solid lines) corresponds to $M_{\text{mc}} = 10^{-13} M_{\odot}$, while the lower pair (dashed lines) to $M_{\text{mc}} = 10^{-12} M_{\odot}$. Within each pair the thick curve corresponds to the age of the stellar Galactic disc of 12 Gyr, and the thin one to 10 Gyr. As one can see from the plot, for the experiments sensitive to the amplification factors $A \sim 10$ the probability of detection is close to 1.

5 Conclusions

To summarize, we have considered the effect of the tidal streams that are produced in disruptions of axion miniclusters by the encounters with the stars in the Galactic disk. Despite only a few percent of the miniclusters get disrupted by the present time, the much larger volume of

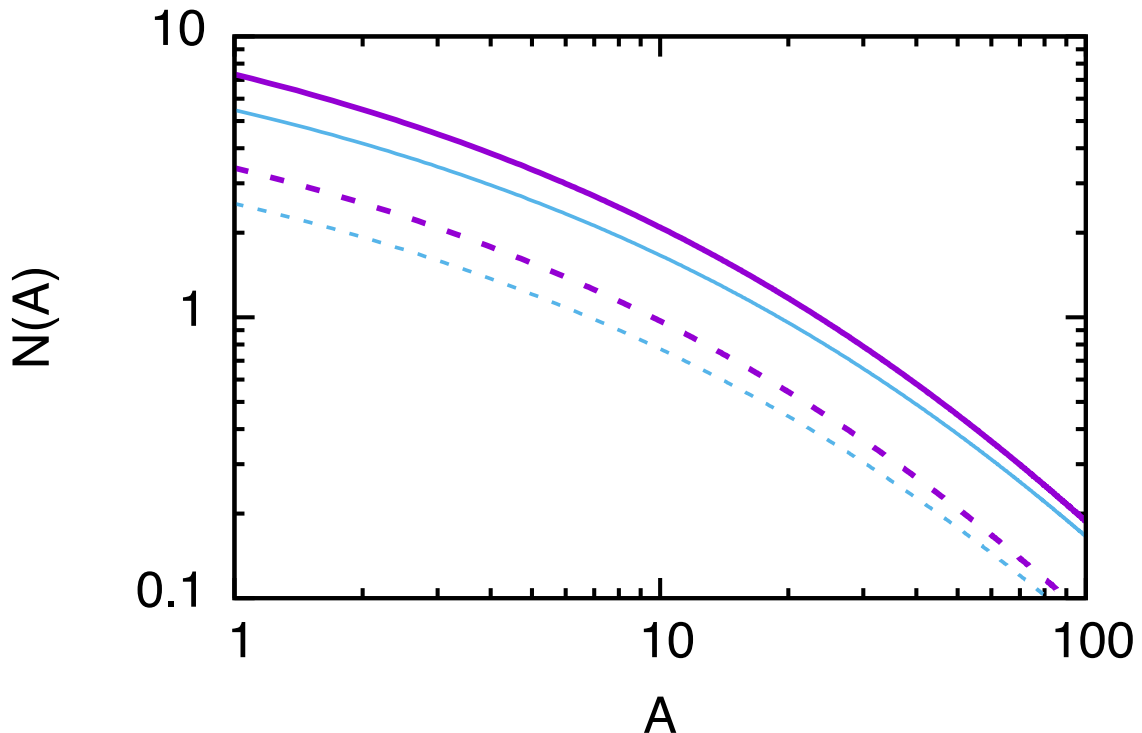


Figure 2. Mean number of encounters with axion streams producing amplification factor larger than A , as a function of A . Twenty year observation interval is assumed. Solid and dashed curves correspond to M_{mc} equal to $10^{-13}M_{\odot}$ and $10^{-12}M_{\odot}$, while thick dark and thin light lines to 12 and 10 Gyr age of the Galactic disc, respectively.

the resulting tidal streams as compared to the miniclusters themselves boosts the encounter rate to an acceptable value of 1 in ~ 20 yr, while still providing a sizeable amplification of the signal $A \sim 10$.

Our estimates have been made in a particular axion DM model where the formation of clumps and their parameters have been studied numerically [4] neglecting the contribution of decaying axion strings and domain walls. This calculation should be improved by including the effects of these structures. We also have made a number of simplifying assumptions: we assumed that all miniclusters have the same mass; we estimated the parameters of the tidal streams rather crudely and neglected their possible dependence on the parameters of the clump orbit; the orbits themselves were assumed to have isotropic distribution around the Earth. A more accurate calculation is clearly needed to take these effects into account.

However, already the present estimate suggests that the effect of the tidal disruption of axion miniclusters may be important for the direct relic axion searches. In particular, our results give extra support for a wide band detection systems. Such systems will not replace of course, but may complement usual narrow axion mass scanning haloscopes. Generically, the latter will not be tuned to the true axion mass during encounter with the region of higher axion density, and the event will be missed. In addition, if miniclusters are abundant, the expected signal between encounters is smaller as compared to the one produced by mean density of axions. This would require extra sensitivity for a resonance detector to

exclude given mass range reliably. Also, the ADMX experiment [21] is slowly scanning an order of magnitude mass range around 10^{-5} eV, while e.g. wide band dish antenna similar to suggested in Ref. [22] may be operational in a much wider range simultaneously, including higher frequencies corresponding to models where axion minicluster formation is expected¹. Wide band detectors might not have sensitivity high enough to detect mean axion background, but may produce detectable signal during encounter event. Clearly, it is not possible to rely on a once-in-twenty-year transient event to identify dark matter. One would need to have at least two such detectors separated geographically. In any case, if axions will be ever discovered, the subsequent search for the rare events, such as tidal stream crossings, will provide valuable information both for the Galactic and the early Universe histories.

6 Acknowledgments

We are grateful to V. Dokuchaev for useful discussions. One of us (K.Z.) wishes to thank Sergio Bertolucci for interesting discussions on dark matter. This work was supported by the Russian Science Foundation grant 14-22-00161.

7 Bibliography

References

- [1] C. J. Hogan and M. J. Rees, Phys. Lett. B **205** (1988) 228.
- [2] E. W. Kolb and I. I. Tkachev, Phys. Rev. Lett. **71** (1993) 3051 [hep-ph/9303313].
- [3] E. W. Kolb and I. I. Tkachev, Phys. Rev. D **49** (1994) 5040 [astro-ph/9311037].
- [4] E. W. Kolb and I. I. Tkachev, Phys. Rev. D **50** (1994) 769 [astro-ph/9403011].
- [5] S. Hofmann, D. J. Schwarz and H. Stoecker, Phys. Rev. D **64** (2001) 083507 [astro-ph/0104173].
- [6] V. Berezhinsky, V. Dokuchaev and Y. Eroshenko, Phys. Rev. D **68** (2003) 103003 [astro-ph/0301551].
- [7] V. S. Berezhinsky, V. I. Dokuchaev and Y. N. Eroshenko, Phys. Usp. **57** (2014) 1 [Usp. Fiz. Nauk **184** (2014) 3] [arXiv:1405.2204 [astro-ph.HE]].
- [8] J. Diemand, B. Moore and J. Stadel, Nature **433** (2005) 389 [astro-ph/0501589].
- [9] H. S. Zhao, J. Taylor, J. Silk and D. Hooper, astro-ph/0502049.
- [10] V. Berezhinsky, V. Dokuchaev and Y. Eroshenko, Phys. Rev. D **73** (2006) 063504 [astro-ph/0511494].
- [11] A. M. Green and S. P. Goodwin, Mon. Not. Roy. Astron. Soc. **375** (2007) 1111 [astro-ph/0604142].
- [12] T. Goerdt, O. Y. Gnedin, B. Moore, J. Diemand and J. Stadel, Mon. Not. Roy. Astron. Soc. **375** (2007) 191 [astro-ph/0608495].
- [13] A. Schneider, L. Krauss and B. Moore, Phys. Rev. D **82** (2010) 063525 [arXiv:1004.5432 [astro-ph.GA]].
- [14] E. W. Kolb and I. I. Tkachev, Astrophys. J. **460** (1996) L25 [astro-ph/9510043].
- [15] O. Wantz and E. P. S. Shellard, Phys. Rev. D **82** (2010) 123508 [arXiv:0910.1066 [astro-ph.CO]].

¹The threshold energy of the dish antenna detector depends inversely proportional on the antenna diameter. For a 10 cm dish size the threshold is about 10^{-4} eV [23]

- [16] K. Kuijken and G. Gilmore, *Mon. Not. Roy. Astron. Soc.* **239** (1989) 605.
- [17] A. Helmi and S. D. M. White, *Mon. Not. Roy. Astron. Soc.* **307** (1999) 495 [astro-ph/9901102].
- [18] H. Lux, J. I. Read, G. Lake, & K. V. Johnston, *MNRAS*, 436 (2013) 2386.
- [19] J. Bovy, *Astrophys. J.* **795** (2014) 1, 95 [arXiv:1401.2985 [astro-ph.GA]].
- [20] G. W. Angus and H. Zhao, *Mon. Not. Roy. Astron. Soc.* **375** (2007) 1146 [astro-ph/0608580].
- [21] S. J. Asztalos, G. Carosi, C. Hagmann, D. Kinion, K. van Bibber, M. Hotz, L. Rosenberg, G. Rybka, J. Hoskins, J. Hwang, P. Sikivie, D. B. Tanner, R. Bradley, and J. Clarke, *Phys. Rev. Lett.* **104** (2010) 041301 [arXiv:0910.5914 [astro-ph.CO]].
- [22] D. Horns, J. Jaeckel, A. Lindner, A. Lobanov, J. Redondo and A. Ringwald, *JCAP* **1304** (2013) 016 [arXiv:1212.2970 [hep-ph]].
- [23] A. Lindner, DESY (2016), private communication.